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Capturing neural correlates of disrupted presence in a naturalistic virtual environment

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Abstract

The concept of presence is commonly related to whether or not a user feels, acts, and reacts as if he/she were in a real familiar environment when using a virtual reality (VR) application. Understanding the neural correlates of presence may provide a foundation for objective measurements of presence and important constraints for theoretical explanations of presence. Discussions about the neural basis for presence are relatively common, but brain imaging has rarely been applied to investigating this issue. Previous studies have focused on detecting average differences between conditions that correlate with differences in reported presence. In this study we focused on breaks in presence and associated periods of disrupted presence as an important complement to previous work. Specifically, we measured brain activity with functional magnetic resonance imaging (fMRI) during execution of an everyday task in a naturalistic virtual environment (VE). Time periods of disrupted presence were identified by subject reports indicating something strange in the current environment, interpreted as a violation of expectations related to the sense of presence. Disrupted presence was associated with increased activity in the frontopolar cortex (FPC), lateral occipito-temporal cortex (LOTc), the temporal poles (TP), and the posterior superior temporal cortex (pSTC). We relate these areas to integration of key aspects of a presence experience, relating the (changing) situation to management of task and goals (FPC), interpretation of visual input (LOTc), emotional evaluation of the context (TP) and possible interactions (pSTC). Modulation of the activity level in these brain areas is consistent with an interpretation of disrupted presence as a re-evaluation of key aspects of a subjective mental reality, updating the synchronization with the virtual environment as previous predictions fail. Such a

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subjective mental reality may also be related to a self-centered type of mentalization, providing a link to accounts of presence building on the self.

Keywords: Presence; brain function; virtual reality; functional MRI.

1. Introduction

Many of the benefits of virtual reality applications are grounded in the ability to make a user act and react as if in a real, naturalistic, environment. This provides a basis for ecologically valid computer applications and enables naturalistic studies of the freely behaving brain (Maguire, 2012). Ecological validity is especially important for applications relating to how the human brain works in everyday life, for example cognitive training, rehabilitation, or diagnosis. In such cases, a primary goal is to allow the cognitive functions of the user to operate as they would in real life. For example, if studying prospective memory using VR, the goal may be to capture the functions that would be at work when setting out to run errands in a real hometown, an everyday task relying heavily on remembering future events (that is, prospective memory; Kalpouzos et al., 2010).

The sense of *presence* is the subjective sense of being “there”, for example when you feel like you are present inside of a virtual environment (VE) rather than in the physical environment of your body. This feeling is tightly related to your ability and tendency to act and react as if the VE was real. Presence can thus be described as the subjective counterpart to ecological validity in VR, which in turn depends on how the brain works in more or less realistic VEs. However, the neural correlates of presence are still unclear. A combination of VR and fMRI has been used in a number of studies over the last decades (Aguirre et al., 1996; Baumann et al., 2003; Hoffman et al., 2003; Lee et al., 2004; Maguire, 2012, 2012; Maguire et al., 1998; Mraz et al., 2003), but only a few have presented results on the neural correlates of presence. Baumgartner et al. (2008) compared two conditions designed to correspond to high and low presence, respectively. Both conditions were presented as non-interactive roller-coaster rides in a 3d-environment, with a flat track in the low presence condition and spectacular slopes and loops in the high presence condition. Questionnaires were used to relate differences in reported presence to differences in brain activation, across subjects. Restricting initial analysis to the prefrontal cortex based on an a priori hypothesis, activity in bilateral dorsolateral prefrontal cortex (DLPFC) was reported as negatively correlated with the sense of presence. Subjects who reported a smaller increase in presence between conditions showed a greater BOLD (blood-oxygen-level-dependent) increase in DLPFC. Using connectivity analysis, DLPFC activity was further related to down-regulation of the egocentric dorsal visual processing stream and up-regulation of the medial prefrontal cortex (MPFC).

The study by Baumgartner et al. illustrates the complexity of isolating the effect of presence among condition differences; requiring an a priori hypothesis as well as analysis of individual differences (based on questionnaires) and connectivity analysis. Bouchard et al. (2012, 2010, 2009) illustrated one way to focus on the subjective experience by using different narratives to manipulate the sense of presence in a virtual environment that was otherwise identical. The reported effect of a narrative promoting presence was restricted to small clusters in bilateral parahippocampal cortex. Still, it remains unclear how neural correlates of presence should be related to the effect of presence in naturalistic VR applications. For example, none of the studies above allowed the user to interact with the environment.

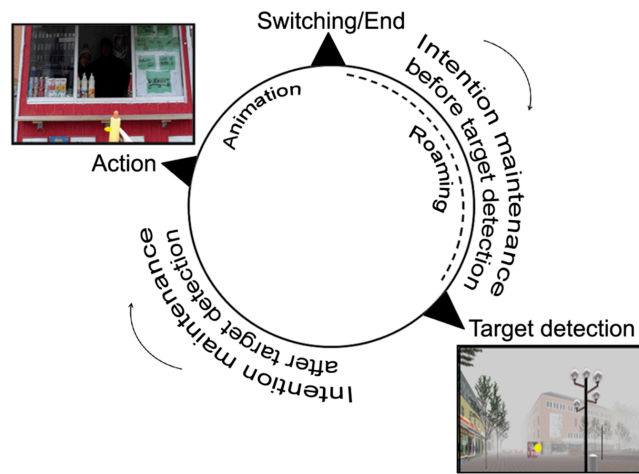
One way to investigate changes in presence in a naturalistic environment is to focus on the phenomenon of “breaks in presence”. The concept of breaks in presence (BIPs) builds on a description of presence as based on the selection of a hypothesis about your environment (Slater and Steed, 2000; Slater, 2002). According to this reasoning the subjective sense of presence depends on accepting a hypothesis about the current (possibly virtual) environment as “real”, and the key factor in maintaining any belief in such a hypothesis (that is, maintaining presence) is to avoid anything that “disproves” it by going against expectations. A focus on BIPs is particularly appropriate to practical VR applications aiming for ecological validity, since BIPs correspond to what you want to avoid in such applications: moments where you are not (re)acting as if in a real environment. Several theoretical accounts of presence and related phenomena elaborate on the importance of expectations and their violation for achieving and maintaining presence, for example, in terms of predictive coding (Seth et al., 2011), simulations in the brain (Riva et al., 2011; Sjölie, 2012), or the importance of being able to rely on expectations and existing motor schemas to be able to “do there” (Jäncke, 2009; Sanchez-Vives and Slater, 2005).

Here, we focus on the effects of BIPs in a naturalistic virtual environment, during a simulated everyday task, in which we did not restrict BIPs to be in accordance with a specific manipulation. Instead, we focused on the subjective experience, and set out to identify time periods where subjects felt that something was “strange” in the virtual reality, that something did not match expectations. Such periods of strangeness match a more general conception of BIPs, relating BIPs to phenomena that are not as expected or do not make sense in the assumed context (reality). Although the BIPs themselves are generally thought of as transient events, the effect of BIPs lingers, leading to periods with a sense of strangeness. Such time periods can be described as *periods of disrupted presence*, related to a mismatch between your subjective mental reality and the virtual reality (Sjölie, 2012). We set out to identify such strange time periods within data recorded during a naturalistic task using a combination of VR, fMRI, and retrospective verbal reports (see Spiers and Maguire, 2006a, for a similar approach). As such, the study has a rare degree of ecological validity since these variations in presence are in a setting where presence is of practical importance for the functioning of the application. Indeed, the fMRI data reported here was recorded while conducting a task designed to study the neural correlates of prospective memory in a naturalistic setting (Kalpouzos et al., 2010).

In a perfect virtual environment, with perfect presence, measured brain activity should correspond exactly to brain activity in a corresponding real setting. Thus, presence-related brain activity would be dictated by the particular task and context. A disruption in presence should then be related to an increased difference between actual activity and the ideal activity for the intended environment and task. For example, in the study by Baumgartner, increased presence while riding a roller-coaster was related to visual and spatial brain regions (Baumgartner et al., 2008). Similarly, in the study by Bouchard, increased presence related to believing oneself to be in a real room was related to activations in parahippocampal cortex, a brain region known to be involved in spatial/location processing (Bouchard et al., 2012).

More generally, accounts of presence as related to predictions in hierarchical models implemented in the brain may provide a framework for interpretation of neural correlates of (disrupted) presence. Such accounts suggest that significant disruptions in presence should lead to increased activity higher up in the hierarchy, corresponding to more frontal brain regions (Seth et al., 2011; Sjölie, 2012). It is also possible to relate disrupted presence to management of disruptions in a task or task switching. The frontopolar cortex (FPC) has previously been implicated in such task management functions (Koechlin and Hyafil, 2007).

A. Prospective memory loop



B. Map of routes



- Starting point of a route
- Location of PM tasks
- Example of a possible route

C. Strange periods within a route

I	C	N	S	N	S	N	C
I = Introduction		C = Calibration		N = Normal interaction		S = Strange time period	

Figure 1. The prospective memory task executed in the VE can be divided into a number of phases (A) that the subject loops through while navigating the VE to locate target objects (B). The analysis conducted in this paper compares brain activity during time periods with reported strange experiences to the time periods with normal interaction during the route (C). Calibration time periods were modeled as a regressor of no interest to improve the statistical model. Images in A and B are adapted from Kalpouzos et al. (2010), with permission.

2. Methods

2.1 Population

Out of 14 subjects in the initial dataset, we selected subjects with at least five *strange* time periods for the present analysis. Eight subjects fulfilled this criterion. The selected subjects were 19-29 (mean 24) years old, and three were female. All but one were right-handed and all had normal or corrected-to-normal visual acuity. None of the subjects had a history of neurological or psychiatric illness. The study was approved by the ethics committee of Umeå University. All participants gave written informed consent to participate.

2.2 Naturalistic prospective memory task

The data analyzed for this study was gathered during the performance of a naturalistic prospective memory task in a virtual environment. The basic task consisted of visiting and activating a number of locations in a 3d-model of downtown Umeå. The experiment was divided into 5 routes. Before each route a list of 4 or 5 tasks (22 in total) was presented to the subjects and the subjects were then allowed to navigate the virtual town freely in order to

locate and complete these tasks. The present study is based on time periods during this free navigation that correspond to disrupted presence, for example, caused by out of date models in some areas of the virtual town. The design of the prospective memory task is described in detail in Kalpouzos et al. (2010).

2.3 The System

The MR-compatible hardware used was a combination of hardware delivered by NordicNeuroLab (Bergen, Norway), and hardware developed in-house at the department of Integrative Medical Biology, Umeå University. The visual system consisted of a set of stereo-capable goggles, SVGA, 800 (x3) x 600 pixels, 16.7 million colors, a horizontal/vertical field of view (FOV) of 30°/23°, with accommodation distance at infinity and a possible diopter correction of -5 to +2 dpt. Eye-tracking was enabled through an integrated camera with an infrared light source, providing a video signal of the right eye. The OLED display used is less sensitive to the electromagnetic fields than alternatives, and all electronics were screened from electromagnetic fields using a Faraday cage. The metal net of the cage was out of focus in the display and introduced very little visual disturbance. The use of these goggles made it possible for the subject to shut out the real-world surroundings in the MR-scanner and become immersed in our virtual environment. The VR-software-system was based on Colosseum3D (Backman, 2005), developed at VRlab, Umeå University. See Kalpouzos et al. (2010) for further details on the system.

By analyzing the right-eye video signal with a computer it was possible to get the positions of the pupil and corneal reflection, and to calculate the gaze fixation point at each time point using calibration data. Eye-tracking data was incorporated directly into the logged data from the VR environment and was projected onto the environment for later analyses. A custom-made joystick was used (right hand) to navigate in the virtual environment. The joystick enabled rotation and movement, separately or as a combined maneuver, in all directions. A pistol-grip type of MR-compatible button was used (left hand) to trigger each task event.

2.4 Verbal protocol

In order to ascertain when subjects experienced disrupted presence while executing a naturalistic task, we used retrospective verbal reports. Subjects were taken into an adjacent room directly after completing the task in the fMRI scanner. After completing some verbal-report warm-up exercises they were instructed to recall and report on their thoughts throughout the experiment in relation to a video replay of their previous interaction with the VR environment. The subject decided the pace of the reporting and the video was paused when needed to give the subject time to elaborate. Interventions by the researcher were otherwise kept to a minimum, restricted to, for example, prompts for clarification. See Spiers and Maguire (2006a) for further details on a similar setup.

When transcribing the verbal protocol we focused on utterances that expressed a sensation that something in the virtual environment was “strange”. Examples of this include “I would not do this in the real world”, “there seems to be something missing here”, and “isn’t there supposed to be a door along this wall”. Initially, we set out to classify utterances into “strange activity” (something happening that felt strange) and “strange environment” (something was strange in the environment) but because of the low number of identified time periods we chose to merge these two categories into a simple “strange” classification covering both types.

Reports were matched to subject behavior based on the video in order to determine the time periods related to specific utterances.

2.5 Neuroimaging Procedure

The current fMRI study was carried out on a Philips 3.0 tesla imaging device (MR-scanner) using an 8 channel SENSE head coil. For the functional scanning the following parameters were used: repetition time (TR): 1512 ms for the first subject and 1500 ms for the following subjects (31 slices acquired), flip angle: 70 degrees, field of view: 22x22 cm, 64x64 matrix and 4.65 mm slice thickness. To avoid signals arising from progressive saturation, ten dummy scans were performed prior to image acquisition. The number of images per subject varied depending on their behavior during the entire task, from a minimum of 754 scans to a maximum of 1109 scans. Structural high-resolution T1 images were also acquired, but they were not used in this analysis. See Kalpouzos et al. (2010) for further details.

2.6 Statistical analysis

For the statistical analysis the brain activity data was treated as a set of images with three dimensions, as is normal for fMRI data. The data from each subject consisted of a series of such images (scans) for all time points throughout the experiment. See Beck et al. (2007) for additional background on basic fMRI data-analysis procedures.

The recorded data was analyzed using SPM8 (Wellcome Department of Cognitive Neurology, London, UK) on Matlab 2011 (Mathworks Inc, MA, US). The pre-processing applied to all images included slice-timing correction, realignment, normalization to standard anatomical space defined by the MNI atlas, and smoothing with an 8.0 mm FWHM Gaussian filter kernel. After resampling, the final voxel size was 2x2x2 mm. To estimate the effect of disrupted presence on brain activity, we used the general linear model (GLM) to create statistical parametric maps with t-statistics. Since the disruptions in presence in our model were in relation to presence during immersive interaction and free navigation in the virtual environment, our primary regressors of interest were *normal* and *strange*, where *strange* corresponds to time periods identified as subjectively strange according to the verbal protocol, and *normal* corresponds to all the time periods with immersive interaction except for the *strange* time periods. To improve the statistical model we also added a regressor for the *calibration* periods before and after the free navigation routes, since these are completely outside of the virtual environment. See figure 1 for an illustration of these time periods during a full route. All regressors were constructed as boxcars convolved with the canonical hemodynamic response function (HRF). We also added regressors of no interest for the motion correction acquired from the realignment pre-processing step. For the estimation of this model we used a high-pass filter with a cutoff of 128 seconds.

Contrasts for a comparison of *strange* versus *normal* were constructed for each subject. These single-subject contrasts, representing the effect of disrupted presence, were entered into a group analysis GLM using the “random effects” option in SPM8. Thus, the resulting group-level difference corresponds to the increased brain activity during periods of disrupted presence compared to normal free navigation, treating subjects as a random variable. This increase is given as t-values describing the size of the effect in relation to the variation between subjects. That is, large activations are effects that are consistently present across subjects. Voxel threshold was set to $p < 0.001$, uncorrected for multiple comparisons, combined with a cluster threshold of extent ≥ 10 voxels.

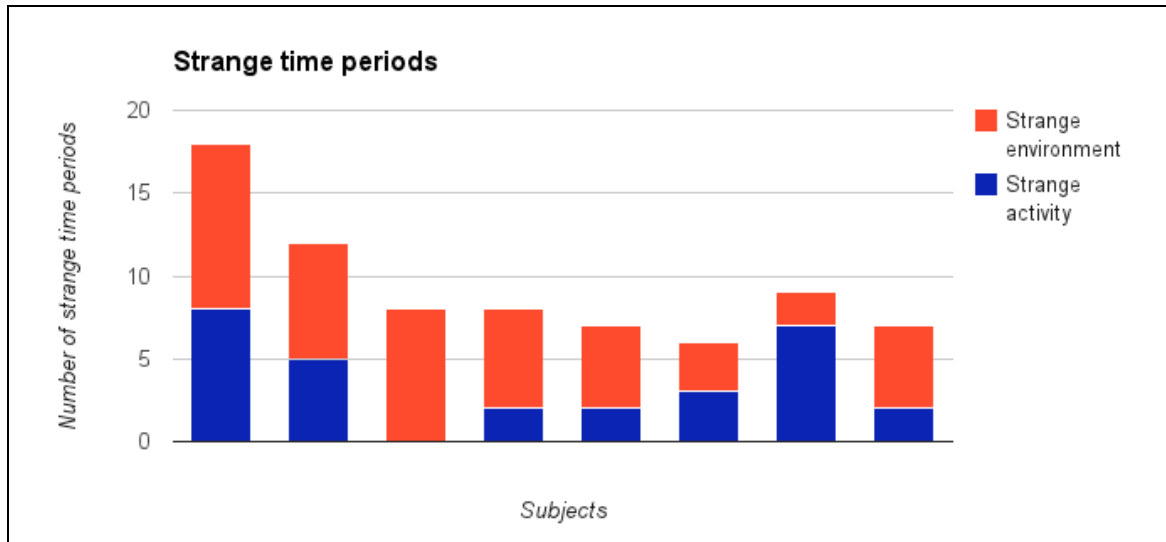


Figure 2. Subjects acted and reported differently, resulting in varying distributions of strange time periods across subjects.

3. Results

3.1 Behavioral results

There were large differences between subjects in how they behaved during free navigation in the virtual environment, and in what they reported verbally about their experience and thoughts throughout the experiment. The distribution of reported *strange* periods, divided into strange environment and strange activity, is illustrated in figure 2. Only subjects with at least 5 periods of disrupted presence were included in the fMRI analysis. This resulted in a dataset of 8 subjects with an average of 9.3 (standard deviation (SD) 3.6) time periods with disrupted presence (*strange*), with an average duration of 4.3 seconds (SD 1.1 seconds). The length of uninterrupted *normal* periods within the routes varied greatly, with an average of 59 seconds and a SD of 58 seconds. As a comparison, one route took 182 seconds on average to complete (SD 50 seconds).

The distance moved per second (via free navigation, measured in VE distance units) was significantly decreased ($p=0.02$) in *strange* time periods (mean 2.3, SD 0.8) compared to *normal* (mean 3.1, SD 0.4) across the group. There were no significant differences for amount of rotation in the VE, or for eye movements.

3.2 FMRI results

Disrupted presence was most strongly associated with increased BOLD signal in the frontopolar cortex (FPC) and in the lateral occipito-temporal cortex (LOTc). Although posterior activations were mostly in LOTc, there was also one smaller cluster in the left inferior parietal cortex. The most dorsal part of the right LOTc cluster encroached on the parietal cortex. There were also smaller clusters in the posterior superior temporal cortex (pSTC) and the temporal poles (TP) in both hemispheres, as well as in left pre- and post-central gyri, orbitofrontal cortex and posterior cingulate gyrus. All identified clusters are

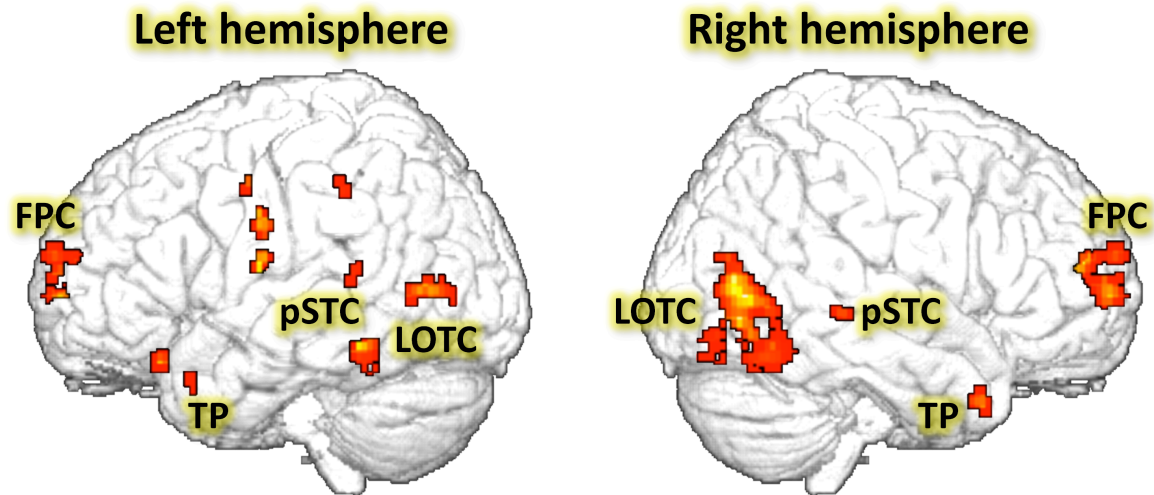


Figure 3. Clusters with increased BOLD signal during periods of disrupted presence (strange compared to normal). Renderings showing activations at a maximum depth of 40 mm projected onto the brain surface, in left and right hemispheres. LOTC = lateral occipito-temporal cortex, pSTC = posterior superior temporal sulcus, TP = temporal pole.

listed with t-values and MNI coordinates for peak voxels in Table 1. There were no regions with significantly decreased activity during *strange* compared to *normal*.

4. Discussion

Based on retrospective verbal reports we were able to uncover the neural correlates of the subjective sense that something (in the static environment or in dynamic events) was “strange”. This is assumed to correspond to a disrupted sense of presence, as these strange events do not match the subjects’ expectations about the environment they are acting in. This conception of presence builds on the tight connection between the context that one believes oneself to be in and the actions that one expects to be able to perform in this context, as emphasized in relation to presence many times before (Jäncke, 2009; Riva et al., 2011; Seth et al., 2011; Sjölie, 2012; Slater, 2009).

4.1 Behavior

While our setup did not actively cause any differences in environment or behavior between the *strange* time periods and *normal* immersive interaction, there may still be consistent differences related to how subjects react during *strange* periods. The only significant difference in behavior was a decreased in-VR-movement during *strange* periods. This may be related to BIPs, as an interruption of the current task may cause the subject to “stop and think” and precludes efficient action.

Brain regions	Brodmann area	x	y	z	Peak T	Cluster size
Frontopolar cortex (FPC)	10/32	2	52	18	13.32	226
	10	-16	62	12	6.69	12
Lateral occipito-temporal cortex (LOTC)	19/37	38	-70	4	12.97	497
	20/37	-46	-46	-14	9.47	81
	19/37	-38	-70	8	8.16	70
Postcentral gyrus	22/43/48	-64	-10	16	10.19	18
	3/4/48	-44	-10	34	8.20	39
Precentral gyrus	6	-34	-6	44	6.83	11
Orbitofrontal cortex	11	-20	26	-20	8.71	16
Temporal pole (TP)	20/38	44	16	-36	7.51	45
	20/38	-34	16	-28	5.26	11
Posterior cingulate gyrus	31	-12	-16	38	7.20	15
Posterior superior temporal cortex (pSTC)	21	46	-34	-2	6.22	12
	22	-56	-44	12	5.50	16
Inferior parietal cortex	40	-48	-40	42	5.51	13

Table 1. Brain regions with significantly increased activity with disrupted presence. Positive x = right, negative x = left. Peak coordinates [x;y;z] in MNI space (Montreal Neurological Institute).

4.2 Activated brain regions

Compared with normal immersive interaction (*normal*), disrupted presence led to increased BOLD signal in a number of brain regions including frontal, temporal, parietal, and occipital cortices. The frontopolar cortex (FPC) has been previously associated with multitasking, in the form of interrupting and postponing a current task, and with decision making related to open-ended and ill-structured situations (Koechlin and Hyafil, 2007). Such cognitive functions match a conception of disrupted presence, and associated BIPs, as a disruption of the current contextual mental simulation, leading to a re-evaluation of input from the environment. The FPC has also been described as “the apex of the executive system underlying decision making” (Koechlin and Hyafil, 2007). This fits well with the view of presence as related to the synchronization of a hierarchical and dynamic mental simulation, driven by expectations and associated prediction errors that are fed upwards in the hierarchy as predictions fail at lower levels (Seth et al., 2011; Sjölie, 2012). By this view, increased activation at the apex of the hierarchy reflects that fundamental assumptions about the current context are challenged, triggering re-evaluation of current interpretations throughout the hierarchy.

FPC has also been related to mentalizing, that is, detecting and thinking about the mental states of individuals, including thoughts, intentions and emotions. While mentalizing has often been related to the human ability to perceive mental states of others, and having a “Theory of Mind” (Frith and Frith, 2003), it has also been related to self-awareness and self-perception (Frith, 2007; Frith and Frith, 2003; Moriguchi et al., 2006). Thus, in the context of the present set-up, with no other people to mentalize about, and in line with the importance of the self in previous accounts on presence (Riva, 2009; Riva et al., 2011), increased FPC activity during the *strange* periods may be related to a form of self-centered mentalizing. Mentalizing has also been related to other brain areas that were activated in the present study, such as the temporal pole (TP) and the posterior superior temporal cortex (pSTC), further supporting the hypothesis of a connection between disrupted presence and mentalizing.

Olson et al. (2007) described the general function of TP as coupling “emotional responses to highly processed sensory stimuli” and linking high-level representations to “visceral

emotional responses”. Such linking can be used both to simulate what might drive the thoughts and actions of other people, as well as for considering the emotional implications of possible situations for oneself. Essentially, the same functions that enable humans to “sense” how others might feel and act in complex situations underlie our own emotional evaluation of the current situation and context (Frith, 2007; Moriguchi et al., 2006). Such a connection between the (virtual) context and our emotional responses is a core aspect of a high level of presence. Note that this concerns the general integration of emotions to context. Which emotions are triggered (and to what degree) may vary greatly, potentially explaining why we have no increased activity in brain areas commonly related to emotions, such as insula and amygdala.

The pSTC is a multimodal region that may be related to many different functions, but one recurring description is involvement in the prediction of complex, often biological, movement and behavior, such as how the body moves. This is an important aspect of mentalizing as it is often used to predict bodily actions of other humans, and the consequences thereof (Frith, 2007; Frith and Frith, 2003; Spiers and Maguire, 2006b). This function may also support prediction of what actions you yourself have available in the current context, which is also a key aspect of successful presence (Slater, 2009). The pSTC is also adjacent to the temporoparietal junction (TPJ), which has previously been implicated in relation to presence (Baumgartner et al., 2008; Jäncke, 2009).

The large LOTC clusters may seem puzzling at first, as these regions are often related to perception of new visual input, typically as a result of changing images or eye-movements (Lee et al., 2000). In our present results, however, we had a decrease in motion during *strange* periods, and no significant change in eye-movements. Instead we are encouraged to consider interpretations related to attention and the context of the visual stimuli. Incongruous visual information has been shown to correlate with increased activity in extrastriate cortex (Michelon et al., 2003), overlapping LOTC, and such an interpretation fits well into a view of disrupted presence as a violation of the “reality hypothesis” and a disruption of the context in which visual information is/was interpreted. In light of theories on brain function that emphasize contextual predictions in a hierarchical and dynamic mental simulation, as described by Seth et al. (2011) and Sjölie (2012) in relation to presence, increased activity in LOTC makes sense, as brain activity is always about the input in relation to contextual expectations.

4.3 Interpretation in context

As mentioned above, presence and subjective realism can be related to the match between a subjective mental reality, corresponding to a hierarchy of dynamic mental simulations, and the virtual environment (Sjölie, 2012). Neural correlates of disrupted presence are likely to vary depending on the specific (virtual) environment and context. In light of this, it is interesting to note that FPC, LOTC, TP and pSTC can all be described as areas providing context and grounding for mental simulations, relating new percepts to overarching goals (FPC), visual input (LOTC), emotional evaluation (TP) and potential interactions (pSTC). In particular, such new percepts may lead to a need to select or switch between multiple tasks (multitasking, FPC), as well as incongruent visual information (LOTC). The possible connection to self-centered mentalizing also highlights the activations in TP and pSTC and suggests a clear link between these results and previous accounts of the self in presence, through visceral personal feelings and possible actions (Riva and Mantovani, 2012; Slater, 2009). In this context, FPC may also be related to personal goals and intentions, given a key role in previous accounts of presence (Riva, 2009; Riva et al., 2011). Note that the two

perspectives suggested here, grounding of a subjective mental reality, and self-centered mentalizing, are compatible. A subjective mental reality is essentially the same thing as the context in which the self acts and perceives, and mentalizing can be described as the simulation of this context. (That is, thinking about the mental states of others is essentially the same thing as simulating their subjective mental reality, in which they may act and perceive the world).

The statistical analysis used in this paper (mass-univariate t-tests) highlights stable differences across the events that together define a condition. Activations related to details of a particular *strange* time period can be expected to vary and not show up as significant in an analysis of an average signal representing all *strange* events. Brain areas providing general context and grounding for subjective mental reality simulations, on the other hand, can be expected to be consistently activated in association with disrupted presence over all different periods and subjects, as subjective reality is re-evaluated and re-grounded.

4.4 Related previous studies

Previous studies by Spires and Maguire (2006b), and Moller et al. (2007) have a similar experimental setup and present similar results, although they do not investigate presence. The results presented by Moller et al. are preliminary, but overlaps FPC and LOTC, and Spiers and Maguire add activations overlapping TP and pSTC to this pattern. On a general level, this illustrates the impact of the specific task and environment for the measured brain activity. In both cases, the attained results may be related to shifting perspectives within a naturalistic environment, during an everyday task. While Spiers and Maguire investigate spontaneous mentalizing, and Moller et al. investigated the effects of naturalistic distractions, such as unexpected movements by other characters in the VE, both these events may be related to a shift (of focus and/or attention) away from the current environment and task, and an associated disruption in presence related to this VE.

Baumgartner et al. (2008) established a relation between a reduced sense of presence and increased activity in the DLPFC, an area that was not revealed in our results. Given the large difference in the experimental setup, it is difficult to be confident about the reason for this mismatch. For example, the time scales are clearly different, measuring either differences in presence over long time periods (including developmental aspects related to presence in children and adults), or the effect of short time periods of disrupted presence. It does, however, seem like our activation in the FPC can be matched to a cluster in MPFC in the study by Baumgartner et al., reported as an area that is up-regulated by the DLPFC and thus related to reduced presence.

While we are not aware of any study using fMRI to investigate neural correlates of BIPs, Rey et al. (2011) used transcranial Doppler (TCD) to measure changes in blood flow volume (BFV) in relation to BIPs. They observed a decrease in BFV related to one out of two conditions designed to elicit BIPs. This should correspond to reduced brain activity, but our results show no significant reduction in brain activity in relation to disrupted presence. However, in the condition that led to reduced BFV an immersive virtual reality with interactive navigation was simply shut down, replaced by a black screen. While it is likely that there was a BIP event as the VR environment disappeared, the difference in brain activity related to perception and interaction with a VR environment, compared to passively watching a black screen, is likely to overwhelm such a difference for a global brain measurement such as TCD. Also, the other BIP condition, disabling free navigation, did not show any consistent differences in BFV.

4.5 Implications

A core aspect of the study presented here is that the experimental design was not explicitly constructed to investigate effects of (disrupted) presence. Although this comes with some drawbacks, it also has some rather unusual advantages, giving an important complimentary perspective to studies comparing levels of presence based on manipulated differences in context or task. Naturalistic studies of the brain aim to investigate the brain when it operates as if the virtual environment was real, that is, with perfect presence. Any imperfections in the virtual environment may lead to disrupted presence, and pose a potential problem that might need to be compensated for. As such imperfections are subjective, in relation to the expectations of the specific user, it may be difficult to identify these through outside observation. Interpreting brain measurements with an understanding of the neural correlates of BIPs may be the most direct and reliable way to compensate for such subjective variation.

Relating our present results to the results from the prospective memory study based on the same data may illustrate how times of disrupted presence may impact the results of brain measurements in naturalistic scenarios. FPC has also been implicated as an important area for prospective memory. It is interesting to note that we get a stronger activation in the FPC in our present analysis, when looking at periods of disrupted presence, than we did for any phase of prospective memory in the previous analysis (Kalpouzos et al., 2010). One possible contributory factor to the lack of strong FPC activity in the prospective memory study may be that the occurrence of periods of disrupted presence in the data introduced variation in the data that was not accounted for. That is, the FPC was activated outside of expected prospective memory phases because of times with disrupted presence, and thus, a comparison involving phases expected to have increased activity in FPC did not show substantial increase. If this is the case, it is a direct illustration of why understanding neural correlates of (disrupted) presence and accounting for it in naturalistic studies is important.

An understanding of neural correlates of (disrupted) presence is also of value for any applications aiming to integrate brain measurements directly, using brain-computer interfaces (BCIs). The possibility to detect disrupted presence via brain measurements could be very valuable both during the development of VR applications and in order to detect problems in running applications. It may even be possible to use adaptive BCIs to automatically adjust computer applications in response to variations in presence, creating a reality-based brain-computer interaction (RBBCI) system where the computer essentially interacts directly with the brain (Sjölie, 2011). Such systems depend on a potential to detect disruptions in presence with objective measures, bypassing the deliberate user. Tracking measurements from the brain areas suggested to provide grounding for subjective mental realities above may be one way forward towards such capabilities.

As mentioned in the introduction, one reason that we focused on periods of disrupted presence instead of BIPs directly was because of limitations in the reliability of the verbal reports. BIPs should correspond to transient events and would require precise timing in order to capture them reliably. Transcription and interpretation of verbal reports unavoidably contain subjective judgments. The relative sparseness of the verbal reports in our study, compared to, for example, Maguire et al. (2006a) adds further uncertainty about the exact timing of identified periods. This sparseness is likely explained in large part by the comparative sparseness of the virtual environment used in this study. For example, while the environment used by Maguire et al. was populated with computer-simulated traffic, the environment used in this study was void of any simulated actors other than the subject. It is also possible that our collection of the verbal protocol was more conservative in the use of prompts for additional information by the researcher. Still, by using time periods instead of

exactly timed events, we are confident that the presented analysis captured important aspects of the neural correlates of disrupted presence.

5. Conclusion

The neural correlates of disrupted presence were captured using fMRI and verbal reports of strange time periods during an everyday task in a naturalistic VE. Increased BOLD responses in FPC, TP, pSTC and LOTC can be related to a general understanding of presence by describing these brain areas as representing important types of grounding for subjective mental reality simulations. In general, the neural correlates of (disrupted) presence can be expected to vary depending on the particulars of the environment and the current task, but accepting immersive interaction in a naturalistic VE as being present in a real place (that is, feeling a sense of presence) may be primarily dependent on specific types of grounding. That is, there are specific types of mental simulations (with corresponding brain areas) that are particularly important for the sense of presence. Current goals (FPC), environmental percepts such as visual input (LOT), emotional integration and evaluation (TP), and interaction possibilities (pSTC), are promising candidates for such groundings. This reasoning is also largely compatible with accounts of FPC, TP and pSTC related to mentalizing, as self-centered mentalizing can be described as tightly related to the simulation of a subjective mental reality.

These results complement studies comparing distinct conditions related to different levels of presence. Importantly, this study has a rare degree of ecological validity in relation to actual usage of VR in naturalistic scenarios, indicating, for example, how measurements of brain activity might be used to track presence dynamically and objectively.

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